

Bounds on new physics from parity violation in atomic cesium[†]

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Abstract

A recent experimental determination of the weak charge of atomic cesium is used to get implications for possible new physics. The new data imply positive upper and lower bounds on the new physics contribution to the weak charge, $\delta_N Q_W$, requiring new physics of a type not severely constrained by the high energy precision data.

1. Introduction

In a recent paper [1] a new determination of the weak charge of atomic cesium has been reported. The most precise parity violating (PV) experiment compares the mixing among S and P states due to neutral weak interactions to an induced Stark mixing [2]. The 1.2% uncertainty on the weak charge Q_W was dominated by the theoretical calculations on the amount of Stark mixing and on the electronic PV matrix elements. In this recent paper [1] the Stark mixing was measured and, incorporating new experimental data, the uncertainty in the electronic PV matrix elements was reduced. The new result

$$Q_W(^{133}\text{Cs}) = -72.06 \pm (0.28)_{\text{expt}} \pm (0.34)_{\text{theor}} \quad (1)$$

represents a considerable improvement with respect to the previous determination [3, 4]

$$Q_W(^{133}\text{Cs}) = -71.04 \pm (1.58)_{\text{expt}} \pm (0.88)_{\text{theor}} \quad (2)$$

On the theoretical side, Q_W can be expressed in terms of the S parameter [5] or the ϵ_3 [6]

$$Q_W = -72.72 \pm 0.13 - 102\epsilon_3^{\text{rad}} + \delta_N Q_W \quad (3)$$

including hadronic-loop uncertainty. We use here the variables ϵ_i ($i=1,2,3$) of ref. [7], which include the radiative corrections, in place of the set of variables S , T and U originally introduced in ref. [8]. In the above definition of Q_W we have explicitly included only the Standard Model (SM) contribution to the radiative corrections. New physics (that is physics beyond the SM)

contributions to ϵ_3 are represented by the term $\delta_N Q_W$. Also, we have neglected a correction proportional to ϵ_1^{rad} . In fact, as well known [5], due to the particular values of the number of neutrons ($N = 78$) and of protons ($Z = 55$) in cesium, the dependence on ϵ_1 almost cancels out.

From the theoretical expression we see that Q_W is particularly sensitive to new physics contributing to the parameter ϵ_3 . This kind of new physics is severely constrained by the high energy experiments. From a recent analysis [9], one has that the value of ϵ_3 from the high energy data is

$$\epsilon_3^{\text{expt}} = (4.19 \pm 1.0) \times 10^{-3} \quad (4)$$

To estimate new physics contributions to this parameter one has to subtract the SM radiative corrections, which, for $m_{\text{top}} = 175 \text{ GeV}$ and for $m_H (\text{GeV}) = 100, 300$, are given respectively by

$$\begin{aligned} m_H = 100 \text{ GeV} & \quad \epsilon_3^{\text{rad}} = 5.110 \times 10^{-3} \\ m_H = 300 \text{ GeV} & \quad \epsilon_3^{\text{rad}} = 6.115 \times 10^{-3} \end{aligned} \quad (5)$$

Therefore new physics contributing to ϵ_3 cannot be larger than a few per mill. Since ϵ_3 appears in Q_W multiplied by a factor 102, this kind of new physics which contributes through ϵ_3 cannot contribute to Q_W for more than a few tenth. On the other side the discrepancy between the SM and the experimental data is given by (for a light Higgs)

$$Q_W^{\text{expt}} - Q_W^{\text{SM}} = 1.18 \pm 0.46 \quad (6)$$

where we have added in quadrature the uncertainties. Therefore the 95% CL limits on $\delta_N Q_W$ are

$$0.28 \leq \delta_N Q_W \leq 2.08 \quad (7)$$

For increasing M_H both bounds increase. These bounds have been used recently [10, 11] to get implications on new physics and will be reviewed here.

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2. Bounds on new physics

Let us now look at models which, at least in principle, could give rise to a sizeable modification of Q_W . In ref. [12] it was pointed out that models involving extra neutral vector bosons coupled to ordinary fermions can do the job. The high energy data at the Z resonance strongly bound the $Z - Z'$ mixing [13]. For this reason we will assume zero mixing in the following calculations. In this case $\delta_N Q_W$ is completely fixed by the Z' parameters:

$$\delta_N Q_W = 16a'_e[(2Z + N)v'_u + (Z + 2N)v'_d] \frac{M_Z^2}{M_{Z'}^2} \quad (8)$$

a'_f, v'_f are the couplings Z' to fermions.

We will discuss three classes of models: the left-right (LR) models, the extra-U(1) models, and the so-called sequential SM models (that is models with fermionic couplings just scaled from those of the SM).

Table 1. Vector and axial-vector coupling constants for the determination of $\delta_N Q_W$ for the various models considered in the text. The different extra-U(1) models are parameterized by the angle θ_2 , and in the table $c_2 = \cos \theta_2$, $s_2 = \sin \theta_2$. This angle takes a value between $-\pi/2$ and $+\pi/2$.

Extra-U(1)	LR
$a'_e = \frac{1}{4}s_\theta \left(-\frac{1}{3}c_2 + \sqrt{\frac{5}{3}}s_2 \right)$	$a'_e = -\frac{1}{4}\sqrt{c_{2\theta}}$
$v'_u = 0$	$v'_u = \frac{\left(\frac{1}{4} - \frac{2}{3}s_\theta^2 \right)}{\sqrt{c_{2\theta}}}$
$v'_d = \frac{1}{4}s_\theta \left(c_2 + \sqrt{\frac{5}{3}}s_2 \right)$	$v'_d = \frac{\left(-\frac{1}{4} + \frac{1}{3}s_\theta^2 \right)}{\sqrt{c_{2\theta}}}$

In the case of the LR model we get a contribution

$$\delta_N Q_W = -\frac{M_Z^2}{M_{Z'}^2} Q_W^{SM} \quad (9)$$

For this model one has a 95% lower bound on $M_{Z'}$ from Tevatron [14] given by $M_{Z'} \geq 630 \text{ GeV}$.

A LR model could explain the data allowing for a mass of the Z' varying between the intersection from the 95% CL bounds $540 \leq M_{Z'}(\text{GeV}) \leq 1470$ deriving from eq. (7) and the lower bound of 630 GeV .

In the case of the extra-U(1) models the CDF experimental lower bounds for the masses vary according to the values of the parameter θ_2 which parameterizes different extra-U(1) models, but in

general they are about 600 GeV at 95 % CL [14] (see Fig. 1). From eq. (8) we can easily see that the models with θ_2 in the interval $-0.66 \leq \theta_2(\text{rad}) \leq 0.25$ give $\delta_N Q_W \leq 0$, and therefore they are excluded at the 99% CL. In particular the models known in the literature as η (or A), which corresponds to $\theta_2 = 0$, and ψ (or C), which corresponds to $\theta_2 = -0.66$, are excluded.

The bounds on $\delta_N Q_W$ at 95 % CL can be translated into lower and upper bounds on $M_{Z'}$. The result is given in Fig. 1, where the bounds are plotted versus θ_2 . In looking at this figure one should also remember that the direct lower bound from Tevatron is about 600 GeV at 95% CL. The χ (or C) model, corresponding to $\theta_2 = 0.91$, is still allowed.

The last possibility we consider is a sequential SM. In this case we assume that the couplings are the ones of the SM just scaled by a common factor a . Therefore we get

$$\delta_N Q_W = a^2 \frac{M_Z^2}{M_{Z'}^2} Q_W^{SM} \quad (10)$$

We see that no matter what the choice of a is, the sign of the new physics contribution turns out to be negative. Therefore all this class of models are excluded at 99% CL.

Finally we have considered certain models based on extra dimensions which have a tower of Kaluza-Klein resonances of the W and Z with masses in the TeV range [15, 16]. These large extra dimensions appear in the string theory context or as a framework to break supersymmetry. In the more general case with two higgs (one in the bulk and one on the wall) PV data put a lower limit on the mixing angle of the KK modes with the SM gauge bosons allowing only the region of maximal mixing [17] ($\sin \beta \geq 0.707$ at 95% CL).

Another interesting possibility one can analyze is that of a four-fermion contact interaction, which could arise from different theoretical origins. Also this case has no visible effects at the Z peak. We will follow the analysis and the notations of ref. [18]. In this situation it turns out to be convenient to express the weak charge as

$$Q_W = -2[c_{1u}(2Z + N) + c_{1d}(Z + 2N)] \quad (11)$$

where $c_{1u,d}$ are products of vector and axial-vector couplings. We will consider models with a contact interaction given by

$$\mathcal{L} = \pm \frac{4\pi}{\Lambda^2} \bar{e} \Gamma_\mu e \bar{q} \Gamma^\mu q, \quad \Gamma_\mu = \frac{1}{2} \gamma_\mu (1 - \gamma_5) \quad (12)$$

This leads to a shift in the couplings given by

$$c_{1u,d} \rightarrow c_{1u,d} + \Delta C, \quad \Delta C = \mp \frac{\sqrt{2}\pi}{G_F \Lambda^2} \quad (13)$$

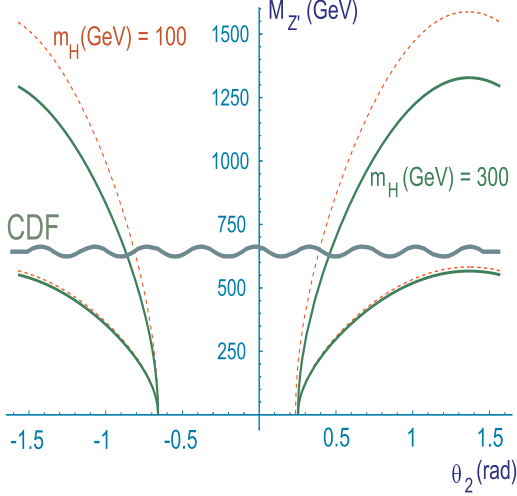


Figure 1. The 95% CL lower and upper bounds for $M_{Z'}$ for the extra-U(1) models versus θ_2 . The continuous and the dashed lines correspond to $m_H = 100$ GeV and $m_H = 300$ GeV respectively. CDF lower bound is also shown.

Since a variation of the couplings induces a variation of Q_W of opposite sign, we see that the choice of the negative sign in the contact interaction is excluded. In the case of the positive sign, using the 95% CL bounds given in eq. (7), we get $12.1 \leq \Lambda^+(TeV) \leq 32.9$ to be compared with the PDG limit $\Lambda^+(TeV) \geq 3.5$ TeV.

Let us now consider a contact interaction induced by lepto-quarks. Following again ref. [18], we take the case of so-called $SU(5)$ -inspired leptoquarks, leading to the interaction

$$\mathcal{L} = \frac{\eta_L^2}{2M_S^2} \bar{e}_L \gamma_\mu e_L \bar{u}_L \gamma^\mu u_L + \frac{\eta_R^2}{2M_S^2} \bar{e}_R \gamma_\mu e_R \bar{u}_R \gamma^\mu u_R \quad (14)$$

From the constraints on $\pi_{e2}/\pi_{\mu2}$ one expects $\eta_L \approx 0$ or $\eta_R \approx 0$. Only the coupling c_{1u} has a shift

$$c_{1u} \rightarrow c_{1u} + \Delta C, \quad \Delta C = \mp \frac{\sqrt{2}\eta_{L,R}^2}{8G_F M_S^2} \quad (15)$$

It follows that the shift on Q_W is negative for $\eta_R \neq 0$. Therefore only the left coupling is allowed ($\eta_R = 0$). In that case we get the bounds (again from eq. (7)) $1.7 \leq M_S(TeV)/\eta_L \leq 4.5$. If one assumes $\eta_L^2 \approx 4\pi\alpha$, it follows $0.5 \leq M_S(TeV) \leq 1.2$.

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